Stretchis: Fabricating Highly Stretchable User Interfaces

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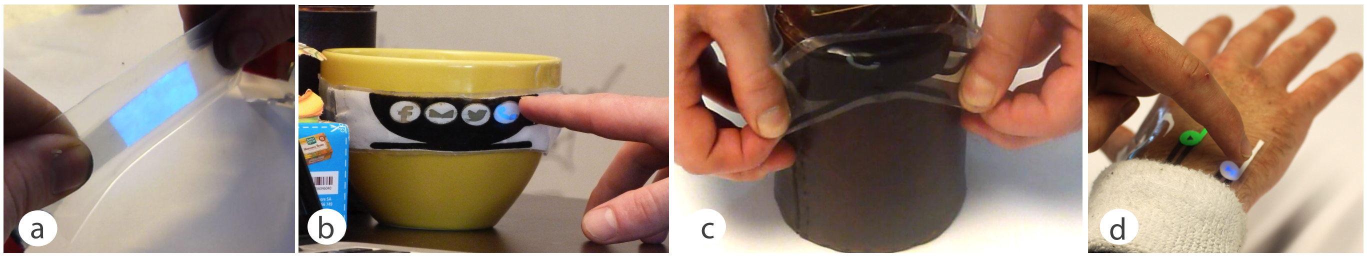

Figure 1. ***Stretchis*** **are highly stretchable user interfaces that include touch and proximity sensors and electroluminescent displays (a).** ***Stretchis*** **are transparent (b); can be stretched to fit to the geometry of different physical objects (c); and can act as on-skin user interfaces (d).**

ABSTRACT
Recent advances in materials science research have enabled the production of highly stretchable sensors and displays. However, such technologies are not yet accessible to non-expert makers. We present a novel and inexpensive fabrication method for creating *Stretchis*, highly stretchable user interfaces that combine sensing capabilities and visual output. We use Polydimethylsiloxan (PDMS) as the base material for a *Stretchi* and show how to embed stretchable touch and proximity sensors and stretchable electroluminescent displays. Stretchis can be ultra-thin ($\approx$ 200 μm), flexible, and fully customizable, enabling non-expert makers to add interaction to elastic physical objects, shape-changing surfaces, fabrics, and the human body. We demonstrate the usefulness of our approach with three application examples that include ubiquitous computing, wearables and on-skin interaction.

Author Keywords
Stretchable interfaces; personal fabrication; sensing technologies; custom-shaped displays; wearables.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation

INTRODUCTION
Early user interfaces separated input hardware (keyboard, mouse, stylus) from output displays. Later research moved beyond dedicated input devices, detecting touch on everyday objects and the human body [21]. Today's smartphones and tablets combine input and output, allowing users to interact directly via multi-touch displays. Unfortunately, these technologies are rigid, expensive and complex to manufacture.

What if we could create inexpensive, lightweight, interactive surfaces that can be embedded in or attached to nearly any physical object? We are particularly interested in ultra-thin, *stretchable* user interfaces that can embed rich interaction onto a wide variety of objects. To this end, we need ultra-flexible and stretchable substrate materials that can adapt to complex object geometries, doubly curved and shape-changing surfaces, and fabrics. We also need highly deformable sensors and displays that remain functional even when the underlying substrates are under strain.

Recent research on printed electronics has made considerable progress in this direction, but has not yet reached a complete solution. For example, iSkin [28] sensors allow limited stretching, up to 30%, but do not provide visual output. Other research [20] demonstrates how to print flexible electroluminescent displays, but the fabrication approach does not support stretchable substrates.

This paper offers a set of key innovations toward our goal of creating inexpensive, ultra-thin, *stretchable* user interfaces. We introduce *Stretchis*: stretchable, fully customizable interfaces for physical objects and fabrics. As in previous research [18, 28], we use silicon-based organic polymers (PDMS) as the base material for embedding sensors. However, we introduce a different fabrication method that supports both *sensor input* (touch and proximity) and *visual output*. In particular, we present a novel multilayer screen-printing method that extends the PrintScreen [20] approach.

Our method deals with the hydrophobicity of PDMS [7, 9], which allows printing of transparent water-based conductive inks on stretchable silicon-based substrates. Makers can create complex multilayer *Stretchi* components digitally by using common design tools such as *GradSoft EAGLE* and

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Adobe Illustrator. They can also customize the visual aesthetics by adding inks of arbitrary colors and shapes, without interfering with the interactive components.

Stretchis can be very thin ($\approx 200\ \mu m$) and can be produced in large formats and at low cost. They are rollable, foldable, and stretchable. We show that *Stretchi* sensors and displays remain functional even when their length is doubled, stretching over 100%. We demonstrate how these features can add interactivity to diverse surfaces, including fabrics, shape-changing surfaces, and human skin.

In summary, our key contributions are:

1. We show how to embed sensor input and visual output in transparent and highly stretchable silicon-based substrates by using a novel, inexpensive fabrication method that even non-expert makers can use. Our method deals with the hydrophobicity of PDMS, allowing to print water-based conductive inks on silicon-based substrates.
2. We introduce a multi-layer fabrication approach for printing displays, capacitive sensors, and aesthetics such that sensors and displays are independent and do not interfere with each other. We demonstrate the usefulness of our approach by fabricating stretchable prototypes that cover ubiquitous, mobile, and on-skin interaction.
3. We evaluate the behavior and reliability of our stretchable sensors and displays under variable strain configurations and show that they can be stretched by more than 100%.

RELATED WORK

Our work combines results from materials science on stretchable electronics and research on methods for prototyping and fabricating flexible sensors and displays.

Stretchable Electronics

Research on fabricating elastic electronics includes electrically conductive fluids [12] and gels that can be embedded in stretchable substrates [10]. Other elastic circuit technologies are based on rigid conductors such as nanotubes [4], graphene [13], and wavy circuit wiring [15]. Other researchers [25, 17] produce transparent circuits by depositing poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) on PDMS. Although most of this research focuses on new materials and methods for creating stretchable conductors, Lu et al. [18] presented rapid techniques for fabricating a variety of laser-patterned conductive material on thin films of PDMS, including silver or carbon-filled PDMS (cPDMS), EGaln, and transparent PEDOT:PSS ink. Elastic electronics support a variety of applications, such as deformable input devices [2] and stretchable keyboards [30].

A few researchers have investigated stretchable OLEDs [23], electrochromic [31], and electroluminescent [27] displays. Others [26, 32] have created transparent and highly stretchable (up to 1500%) electroluminescent devices based on ionic hydrogel conductors which exhibit impressive strain resistance. However, these are less conductive than electronic conductors, and it remains unclear how to adapt these fabrication methods for non-expert makers.

We are inspired by stretchable electronic conductor research by Lipomi et al. [17], Lu et al. [18], and Wang et al. [27]. However, we use a more flexible fabrication method for printing transparent PEDOT:PSS sensors on stretchable PDMS substrates in combination with electroluminescent displays. Our method does not require specialized treatments or laser engravers to dispose and pattern the conductive material, making it better adapted for quick prototyping by designers, non-expert practitioners, and Human-Computer Interaction (HCI) researchers.

Fabricating Flexible Sensors and Displays

HCI researchers are increasingly interested in flexible sensors and displays. For example, Savage et al. [22] created a toolkit to support the design, fabrication, and programming of flexible copper-based capacitive sensors. Kawara et al. [11] introduced a rapid-prototyping approach for printing conductive ink on paper with off-the-shelf inkjet printers. Gong et al. [8] extended this approach to allow for a larger range of sensing capabilities, including proximity, pressure, and folding. More recently, Dementyev et al. [6] demonstrated a flexible and cuttable sensing tape that carries a dense array of sensors and other electronic components.

The above approaches support use of flexible, e.g., foldable and bendable, yet non-stretchable substrates. To this end, Sugiura et al. [24] produced a thin elastic interface made of stocking fabric that can sense deformations caused by pressing or stretching the fabric.

Inspired by Lu et al. [18], Weigel et al. [28] introduced a fabrication method for integrating customizable carbon-based press and touch sensors into stretchable PDMS substrates. They can laser-engrave custom patterns of conductive material into PDMS and showed that their sensors are still usable even if they are stretched by 30%. The key limitation is the reliance on back carbon-based conductive ink, which is incompatible with printable displays and limits the designers' freedom to customize the interface.

Previous HCI work on flexible displays has focused primarily on integrated devices [16] rather than on solutions for fabricating custom-made displays. The PrintScreen framework [20] was the first to make fabrication of interactive electroluminescent displays accessible to non-expert makers. Their approach is applicable to a variety of flexible substrates, including paper, leather, and ceramics. Our fabrication method extends this work to include new applications with highly stretchable transparent substrates, allowing greater flexibility and freedom when designing and instrumenting interactive sensors.

STRETCHIS: REQUIREMENTS AND CHALLENGES

The key requirements and challenges for fabricating *Stretchis* include:

Form Factor. *Stretchis* must resist strain and remain interactive when adapted to a wide variety of objects. For example, makers may want to add interaction to curved surfaces, such as a door handle; deformable objects, such as a lamp's flexible neck; elastic joints, such as a mobile phone cover; as well as their own clothing or bodies.

Substrate Properties. The base material of a *Stretchi* must be able to host sensors and displays but also expose its physical properties and affordances, such as its thickness, flexibility, and stretching behavior. PDMS is inexpensive, malleable and especially suitable for fabricating flexible and transparent substrates for printed electronics [18, 28]. Given these properties, we decided to use PDMS as the base material for *Stretchis*.

Input and Output Capabilities. *Stretchis* must accommodate both sensors and displays in the same stretchable substrate. Olberding et al. [20] use layers of transparent conductive ink to illuminate a layer of phosphor and to sense touch. However, their fabrication method does not support *stretchable* silicon-based substrates, because PDMS is hydrophobic and thus incompatible with water-based conductive inks. Another limitation is the use of the same layer of conductive ink to support both illumination and touch sensing, which significantly constrains the design of input and output widgets on interactive surfaces.

Fabrication Process. *Stretchis* should support rough prototyping and encourage customization, especially for users without access to cutting-edge equipment: (i) HCI practitioners who must quickly prototype interactive devices and ubiquitous interactive displays; (ii) designers who work on artistic installations, create wearables for interactive performances, or bring interaction to sharable objects and public spaces; and (iii) hobbyists who want to add interactive parts to their fabricated objects.

MULTI-LAYER FABRICATION APPROACH

The *Stretchi* platform includes four functional layers that serve as the building blocks for each customizable interface:

1. *Base Substrate Layer* – serves as the base material, consisting of pure PDMS, that provides stability and determines the physical properties of the interface, including thickness, color, and stretching behavior, as well as support for embedding *Stretchi* interfaces into porous materials, such as fabrics.

2. *Sensing Layer* – consists of a layer of conductive ink that adds sensing capabilities, patterned and shaped according to the specific input requirements. *Stretchis* currently support touch and proximity sensing.

3. *Display Layer* – provides electroluminescent visual output. Each display layer is composed of two layers of conductive ink, two layers of binding ink, and a layer of a phosphor/PDMS mix which emits light.

4. *Aesthetics Layer* – consists of colored inks in arbitrary 2D shapes to add visual effects to the interface.

The multi-layer approach increases flexibility, since layers are independent and can be customized and printed during different phases of the fabrication process. Figure 2 shows representative *Stretchi* structures, where layers can be stacked in different ways. A *Stretchi* can contain several layers of the same type, such as two sensing layers dedicated to different types of sensing or different user interface components.

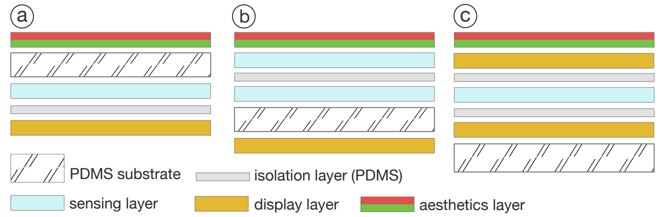

Figure 2. Three sample variations of *Stretchi* multi-layer structures. The top layer is the *Stretchi* viewing surface.

The choice of structure depends upon the specific requirements of the *Stretchi* application. For example, proximity sensors are more precise when placed near the *Stretchi*'s surface. Stacking multiple sensing and display layers on top of each other requires an intermediate PDMS-based layer to isolate their conductors. A *Stretchi's* overall thickness can be as little as 200 μm and is largely determined by the thickness of the base substrate. The typical thickness of all the printed layers, without the base substrate, is between 50 and 100 μm.

Adding Stretchable Conductors to PDMS

The stretchable base material places special demands on the ink, which must not only be conductive, but stretch without failing. We could apply other methods for fabricating stretchable sensors based on liquid metal (EGaIn) conductors [18] and carbon-filled PDMS (cPDMS) [18, 28] to the *Stretchi's* sensing layer. Unfortunately, these inks are not transparent, which limits the display and aesthetic possibilities; and the methods require expensive specialized equipment, such as a laser engraver, to print the conductive material.

First, the conductors are not transparent – this constrains the way someone designs and adds displays and aesthetics to the interface. Second, to pattern conductive material, these methods rely on specialized equipment such as laser engravers – yet, our goal was to avoid imposing the use of such equipment.

Other studies of stretchable materials [25, 17] indicate that transparent conductive inks based on PEDOT:PSS (GWENT D2070209P6) can be added to stretchable PDMS surfaces and are resilient to strain. In particular, Lipomi et al. [17] report that PEDOT:PSS films retain conductivity even after a strain of over 100%, where 188% is the break point. In addition, for strain levels up to 30%, these films are reversibly stretchable, where resistance increases by a factor of 5 after 1000 stretches. However, applying PEDOT:PSS on PDMS requires specialized treatments difficult to integrate into a lightweight fabrication process. Applying water-based inks such as PEDOT:PSS on PDMS substrates is especially challenging because the surface of PDMS is hydrophobic. Printed shapes lose their homogeneity, and the liquid ink forms drops on the surface of the PDMS (similar to the *lotus effect*).

Simple methods for treating the surface to increase water acceptance include corona [9] and plasma treatments [7]. Unfortunately, these methods require highly specialized equipment and laborious procedures. Moreover, the effect is temporary: depending upon the method, the surface becomes hy-

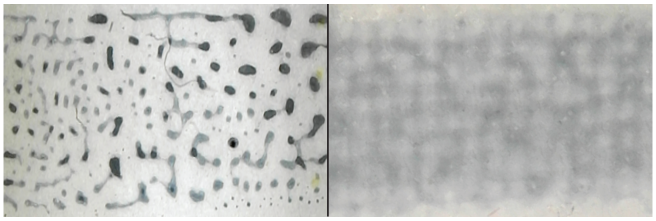

Figure 3. Printed layer of PEDOT:PSS on PDMS recorded under 20x magnification. Left: Without the binding layer, the liquid ink forms drops and the layer is not conductive. Right: A binding layer printed between PDMS and PEDOT:PSS. The ink forms a connected layer and is conductive. The screen printing mask pattern is visible.

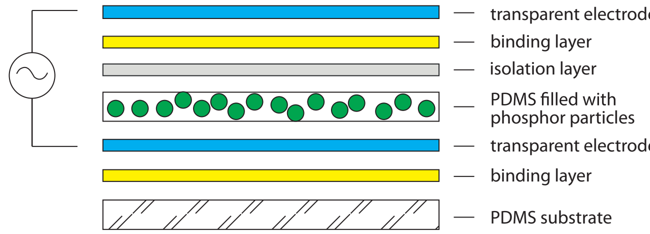

Figure 4. Schematic of a stretchable display printed directly on a PDMS substrate. A phosphor/PDMS layer is sandwiched between two transparent conductive layers (electrodes) of PEDOT:PSS. Binding layers allow for printing the conducive layers on PDMS.

drophobic again in a few minutes to one hour. This complicates the printing process and hinders usability of the fabricated sensors, especially if the PEDOT:PSS ink peels off. The plasma treatment permits a maximal stretching of 10% before a critical breakdown occurs [17].

After experimenting with various treatments, we developed a simple, inexpensive and permanent method for applying water-based inks onto hydrophobic surfaces such as PDMS. Since direct application of the conductive ink is not possible, we use a stretchable binding layer as an interface between the PDMS and the ink. *AQUAPLAST-DIY Transparent Binder* is an inexpensive ($< \$15/kg$), off-the-shelf transparent ink commonly used for fabric printing. Not only does it have excellent printing properties on PDMS, it remains fully stretchable. This transparent binder contains a lower percentage of water than the PEDOT:PSS ink, which reduces the repellent effect. Also, because it is highly viscous, the ink does not form drops on the PDMS surface, making it suitable as as a base for applying conductive ink.

Figure 3 compares two different prints: (Left) water-based ink printed on pure PDMS, and (Right) the same ink printed on PDMS through a binding layer. Note that the print pattern of the transparent conductive material on pure PDMS is disconnected and has many holes. The binding layer allows the conductor to be printed homogeneously.

Embedding Stretchable Displays

Since we can now add transparent conductive inks on PDMS, we can also extend Olberding et al.'s method [20] and print electroluminescent displays on stretchable PDMS substrates. The general principles of electroluminescence are simple [14]: Phosphor particles are sandwiched between two electrodes. Applying an AC voltage to the electrodes establishes an electric field between the two plates, which activates the phosphor particles and causes them to emit light. The method offers great freedom for the design and customization of ubiquitous interactive displays [20].

We adapt Wang et al.'s [27] fabrication method to produce a stretchable phosphor layer. First, we mix phosphor particles (KPT D310B) into fluid transparent two-component silicon in a ratio of 2 to 1, and screen print the mix. After curing, the layer is stretchable and connects directly to the underlying layers. Each stretchable display is composed of five or six sub-layers (Figure 4). The phosphor/PDMS mix is printed between two layers of conductive material made of stretchable transparent ink. As explained earlier, we must also print a binding layer for each conductive layer. We then print an isolation (PDMS) layer on top of the phosphor layer to protect the two conductive layers from electrical breakdowns.

Sensing

We adapt Olberding et al.'s [20] time-multiplexing approach to avoid interference between electroluminescent displays and attached sensing layers. The display is deactivated during the sensing cycle by turning off its energy supply and setting both its electrodes to high impedance. In the current implementation, internal capacitors take $1.7\ ms$ to discharge. The *Stretchi* is then free of electric noise, allowing us to choose from a variety of sensing methods.

For touch and proximity sensing, we use Arduino's Capacitive Sensing Library [3]. One sensing cycle takes less than $2\ ms$, resulting in $3.7\ ms$ total turn-off time for the display. To avoid flicker, we turn on the display for $10\ ms$. This corresponds to a frame rate of 73 Hz, which is not visible to the human eye. Deactivation of the display leads to a 27% reduction in brightness. We compensate for this either by increasing the display's AC voltage or the AC signal's frequency.

Although we currently demonstrate only touch and proximity sensing, our fabrication approach can accommodate other sensing techniques for printed electronics. For example, we could apply one-layer [8] or multi-layer sensing methods [29] to sense pressure, folding or stretching. A major strength of our approach is that *Stretchi* sensors are designed and printed independently of each other and of the display. Unlike Olberding et al.'s [20] method, the display does not constrain the number, geometry or layout of the sensors.

Fabrication Process

The *Stretchi* fabrication process consists of five basic steps:

Design the *Stretchi* – The designer uses graphic design software such as *Adobe Illustrator* or *Gimp* or circuit design software, such as *EAGLE*, to draw the components of the interface (Figure 5a). Each virtual layer corresponds to physical *Stretchi* structures: the PDMS substrate, the sensors, the displays, and the aesthetics or graphical features (see Figure 2). Binding and isolation layers are normally larger than the transparent conductors to ensure that the conductors are well covered and thus protected.

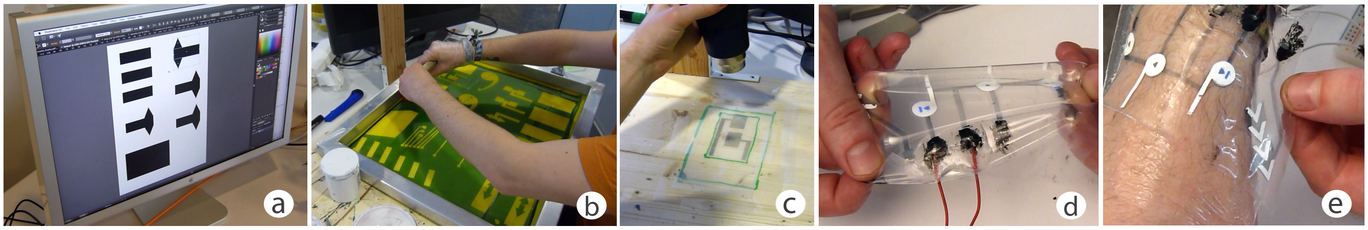

Figure 5. ***Stretchi*** **fabrication process: (a) The designer uses standard design software to create a virtual layer corresponding to each physical** ***Stretchi*** **layer. (b) The shapes in each layer are transferred to a screen printing net, using UV lithography, and then printed onto the stretchable PDMS substrate. (c) Each printed layer is cured or heat-dried before the subsequent layer is printed on top. (d) The designer adds power and (e) tests the** ***Stretchi*****.**

Produce the Stretchable Base Material – Ready-to-print sheets of PDMS of varying colors, elasticity, and thickness (20 - 400 μm) are commercially available, e.g., at Wacker GmbH, at a cost of less than \$10/sheet. However, we can also fabricate custom PDMS substrates with inexpensive materials and tools. We can fully control the form and composition of the PDMS with fluid two-component silicon, which remains liquid for an hour after mixing. The PDMS surface can be shaped by spin coating, molding, or using a thin film applicator, to achieve the desired form and thickness. Color pigments can also be mixed into the silicon to create custom colors. The silicon cures at room temperature in 24 hours or, if placed on a hot plate at 90°C, cures in about 20 minutes.

Print Sensors, Displays, and Aesthetics – We use screen printing [5] to add display and sensing layers to the base layer of the PDMS substrate. Screen printing is a well-known, easy-to-use, and low-cost method for printing functional inks on a variety of substrates. We use a standard off-the-shelf manual screen-printing table that costs under \$200 (Figure 5b). We recommend using high resolution nets (100T - 140T) to ensure high-quality printed shapes.

The designer prints each successive display and sensing layer, with sufficient time between each step for the printed material to cure (Figure 5c) and cool down. A good practice is to move the squeegee fast and with low pressure while printing to protect previously printed layers. Off-the-shelf screen-printing inks, e.g., TEXPRINT-AQ, have properties similar to the binding layer but include opaque or semi-transparent color pigments. The designer can build layers of color to create various visual effects and custom graphic designs.

Shape the ***Stretchi*** – The designer can manually shape the *Stretchi* with scissors or laser cut it for more precise control [18]. To produce 3D shapes such as cylinders or structures that combine multiple *Stretchis* together, the designer can glue them together with fluid silicon or with a special silicon glue.

Add Rigid Electronics, Power, and Control – *Stretchis* may include additional electronic components, such as integrated circuits, LEDs, and various rigid sensors (Figure 5d, 5e). They can also be wired with non-transparent conductive materials, such as cPDMS [28]. Carbon Powder (e.g., Cabot Black Pearls 800) is mixed with fluid PDMS ($8k\Omega/cm^2$) in a ratio of 8%. Before curing, the cPDMS is applied as a connector between a Stretchi and the electronic component. The designer has various options for powering and controlling the *Stretchi*'s sensors and displays. Our prototypes use an Arduino Uno microcontroller.

Displays require high voltage (≈ 150 V) but low-current AC, so we use a compact inverter to transform 12VDC to high voltage AC. The designer can also create mobile *Stretchi* applications by using more compact power and control units. For example, a very small inverter IC (e.g., SIPEX SP4405) can generate AC in combination with a dedicated mobile controller unit, such as an Arduino nano or Intel Curie controller, and be powered with very small button battery cells.

APPLICATION EXAMPLES

How can designers use *Stretchis* to embed interaction onto objects or into the physical environment? We developed several working prototypes to demonstrate possible applications.

We fabricated a stretchable awareness sleeve that fits onto various objects, such as a coffee cup (see Figure 1b), to provide notifications about incoming calls and social media events. The sleeve is equipped with electroluminescent displays that provide visual notifications; and touch sensors that let the user redirect notifications to specified computer applications. We also fabricated an ultra-thin *Stretchi* designed to be worn on the back of the hand; it is stretchable to allow the hand to move (see Figures 1d and 5). The interface provides illuminated control widgets for music player: play, skip, and pause touch buttons, as well as a touch slider to control volume.

Finally, we experimented with *Stretchis* that integrate sensing into stretchable fabric. For example, Figure 6 combines printed conductive ink with rigid electronic components to create a *Stretchi* sport headband notification system. This *Stretchi* includes a rigid vibration motor for sending private notifications to the wearer, who can touch the band to display

Figure 6. A ***Stretchi*** **integrated into a stretchable headband. The** ***Stretchi*** **includes a (1) rigid vibration motor that sends notifications to the wearer and a (2) stretchable touch sensor to support touch interaction.**

them on the screen of a mobile phone. The stretchable headband is easy to slip on and can accommodate various head sizes and hair styles.

TECHNICAL EVALUATION

We ran a series of tests to evaluate the technical behavior, reliability, and robustness of *Stretchi* sensors and displays.

Capacitive Touch and Proximity Sensing

We conducted an experiment to evaluate the touch and proximity sensing behavior of a *Stretchi* under varying levels of strain, where the interface was stretched up to 120%. For comparison, Weigel et al. [28] tested the *iSkin* sensor with an upper limit of 30% strain.

Apparatus. We printed a 15×15 mm rectangular pattern of PEDOT:PSS on a silicon sheet, following the described fabrication approach. We connected the sensor with a printed 1 mm wide conductive line. We took measurements with an Arduino controller.

Participants. 12 volunteers (six women and six men), 21 to 30 years old, participated. All tested the same sensor.

Procedure. For each trial, the participant approached the sensor with the index finger from an angle of $90°$ at seven discrete steps, from a distance of 6 cm to a distance of 0 cm, which corresponds to direct touch. For each distance, they were asked to rest their finger for three seconds. During this time, we used the Arduino Capacitive Sensing Library to record an average of 63 ($SD = 10$) measurements of the sensor's capacitance value.

This process was repeated five times, with the sensor stretched at five different levels: 0%, 30%, 60%, 90% and 120% of its natural length. The experimenter attached the sensor between two clamps and progressively stretched it from 0% to 120%.

Results. Figure 7 summarizes the results. We take the median of all measurements for each unique combination of participant, strain level, and distance. The key finding is that the sensor is extremely resilient to strain: For both touch and proximity sensing, the sensing capabilities of the sensor remain intact.

The high variance of values observed for touch sensing can be largely explained by the variability in the way participants touched the sensor, for example, touching hard versus gently; or touching the center versus the edges of the sensor. However, the transition from 1 cm distance to touch always increased the measured value by at least 453% (by a mean factor of 24). We could thus easily differentiate touch and proximity events, with perfect (100%) recognition accuracy.

The behavior of proximity sensing is consistent across all strain levels (Figure 7b). Proximity sensing is clearest at around 3 cm from the sensor. We could further increase the sensor's sensitivity by applying a larger area of conductive ink. Even though all 12 participants tested the same sensor over two different days, we did not observe any degradation of the sensing values over time.

Luminosity of Displays

We also tested how the brightness of a printed display is affected by different strain levels.

Apparatus and Procedure. We fabricated a rectangular 40×20 mm display. We used the controllable head of a CNC milling machine (with an x and y resolution of 10 $\mu m/$step) to stretch the display (see Figure 8). We applied strains from 0% to 50% and back again to 0% (Figure 7b). We repeated this process 10 times. We used a PYL-ELI-ISC inverter with 12 V DC input and powered the display with 150 V AC at 1.3 kHz frequency. We used a photodiode to measure variations of the light emitted by the display. More precise measures of display luminance require specialized measurement tools; however, this evaluation offers an initial assessment of the reliability of printed *Stretchi* displays.

Results. The sensor measured relative raw brightness values at 13 (0% strain), 17 (30% strain), and 16 (50% strain). All values remained highly stable during all 10 stretching cycles. The increase in brightness when the display is stretched is due to the fact that the voltage is applied to a thinner layer of the phosphor/PDMS mix. The estimated luminance values that correspond to these measurements range between 120 - 200 cd/m^2, which is comparable to the range of values reported by Olberding et al. [20]. Note that all the display layers are transparent, and the display emits light in two directions, towards both the viewing and the hidden surface of the *Stretchi*. The brightness could be increased by printing an additional light-reflective or white layer, under the display.

Durability of Stretchable Conductors

We further tested the extent to which stretchable conductors produced with our approach can endure a large number of stretches while still remaining conductive. We applied a total of 6000 stretches, where for each cycle of stretching, the strain increased from 0% to 50%. The 50% strain value is an upper bound for wearables and on-skin devices in normal use. For comparison, Lipomi et al. [17] tested the durability of their stretchable conductors by applying 1000 stretches from 0% to 30%.

Apparatus and Procedure. We used the described fabrication method to print a 60×6 mm layer of PEDOT:PSS on a 1-millimeter thick PDMS substrate (SORTA-CLEAR 40). The test pattern was sealed with an additional layer of PDMS. We measured an initial, 0% strain, resistance of 2.7 kΩ between the two ends of the test pattern. We then used the controllable head of a CNC milling machine (with an x and y resolution of 10 $\mu m/$step) to stretch the substrate. We applied a strain from 0% to 50% and then back again to 0%. We repeated this process 6000 times.

Results. The resistance increased non-reversibly after the first stretches: 177 kΩ after 10 stretches. As Lipomi et al. [17] explain, this is because the first stretches introduce tiny breaking lines in the conductive layer. These lines are permanent and increase the conductor's resistance, without hindering conductivity. Subsequent stretches had a low impact on the conductor's resistance, reaching a value of less than 350 kΩ after 6000 stretches. This additional increase (< 29 Ω per

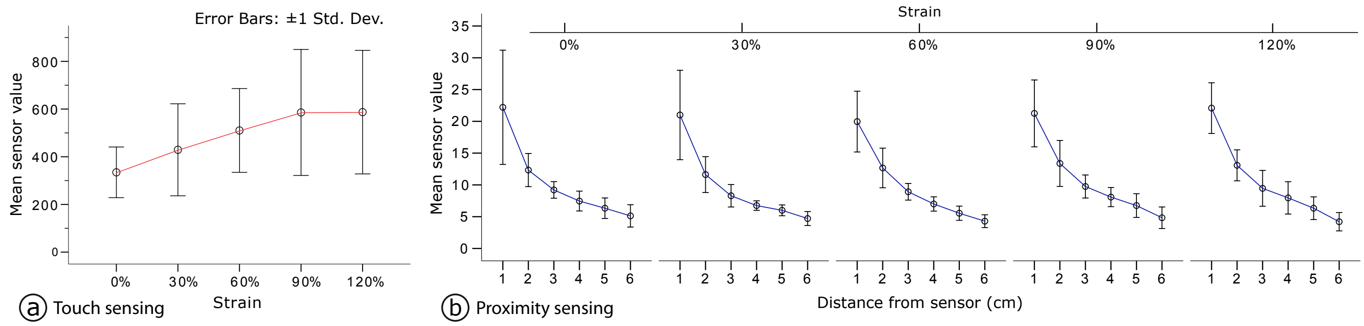

Figure 7. Experimental results for touch (a) and proximity sensing (b) under variable strain (0% – 120%). Sensor values are relative [3], where no sensing corresponds to values close to 0. We show between-participant standard deviations for 12 participants.

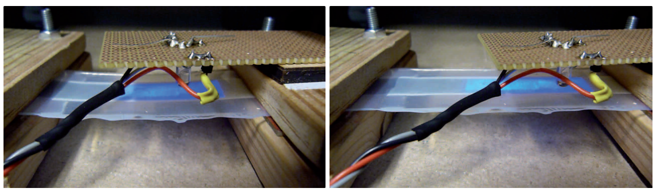

Figure 8. A CNC milling machine strains the *Stretchi* display in order to measure its brightness. Left: 0% stretch. Right: 50% stretch.

stretch on average) is negligible for most capacitive sensing methods. Even so, we cannot reliably detect and measure strain, which requires different sensing technologies. An increase in the conductor's resistance can also reduce the display's brightness but does not hamper its usability in most real-world situations. Of course, we could also increase the voltage supply of the display to compensate for this loss.

Break Point. After the end of the above procedure, we stretched the same patterned substrate until conductivity reached a complete breakdown. This occurred when strain reached the level of 153%, where the resistance exceeded the value of 10 MΩ. Lipomi et al. [17] report a higher break point for their method at 188% strain. However, they used a virgin conductive film for this test, not previously exposed to strain.

DISCUSSION AND FUTURE DIRECTIONS

Our method accommodates multiple conductive and display materials without changing the overall structure of *Stretchi* components. For example, we are interested in using WO_3 powder to support electrochromic [31] as well as electroluminescence displays. Designers can also integrate more conventional electronics as separate layers within a *Stretchi*'s' multi-layer architecture, including non-stretchable or non-transparent components in parts of the interface, e.g., to support richer sensing modalities such as pressing, bending or folding [8, 19].

Results from advanced materials research [1] show that conductors based on silver nanowire (AgNW) networks can be embedded between PDMS layers and produce highly stretchable sensors (up to 70%). AgNW networks are also transparent but have additional interesting properties, i.e. they are more conductive than PEDOT:PSS and can act as strain sensors [1]. Sensing strain is particularly challenging, especially since the change in resistance of PEDOT:PSS conductors is not fully recoverable after stretching. In the future, we plan to produce strain sensors based on AgNW networks and integrate them into our fabrication process. We would also like to extend our approach to accommodate ionic [26, 32] in addition to electronic conductors.

CONCLUSION

We present an inexpensive method for fabricating *Stretchis*, highly stretchable interfaces that combine sensing and display capabilities. This method enables designers and novice makers to embed transparent conductors and electroluminescent displays into stretchable PDMS substrates. Inspired by state-of-the-art research on flexible electronic materials [17, 18, 27], we introduce new fabrication techniques that do not require specialized treatments or expensive equipment. In particular, we show how to prototype stretchable user interfaces by using standard design software and screen-printing techniques. Despite the use of inexpensive equipment, our results demonstrate that we can produce durable and highly stretchable sensors and displays that remain functional under strain levels of greater than 100%. We designed three sample applications that support touch and proximity sensing, but the *Stretchi* fabrication approach is applicable to a variety of additional sensing technologies.

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